

Solar Lunar Power

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ABSTRACT

Current and projected technology is assessed for photovoltaic power for a lunar base. The following topics are discussed: requirements for power during the lunar day and night; solar cell efficiencies, specific power, temperature sensitivity, and availability; storage options for the lunar night; array and system integration; the potential for *in situ* production of photovoltaic arrays and storage medium.

1. INTRODUCTION

Recent evaluation of the power requirements for an initial lunar outpost based on a 4 person crew including a 45 day stay on the lunar surface required 10.8 kW daytime and 9.7 kW nighttime during the crewed phase and 2.0 kW daytime and 2.8 kW nighttime for the uncrewed phase of ~ 4 months.¹ This analysis assumed 8 kW for crew systems, 1.8 kW for avionics, and 1.0 kW for laboratory science experiments. The power requirement profile for a lunar base will not be uniform. To optimally make use of available energy, discretionary energy-intensive activities would be carried out primarily during the daytime. However, some activities, such as life-support, cannot be cut back during the night, and may even require greater energy expenditure at night than during the day (*e.g.*, lighting, including possible requirements for greenhouse lights if a closed life support system is required, science activities such as astronomy). Our analysis will be based on a power requirement of 25 kW of electric power. The driving factor for the selected technology is the mass, due to the high cost of transportation to the lunar surface.

The initial piloted landing will require the availability of power very shortly after the landing, preferably with a minimum of EVA activity required to deploy the power system. Fig. 1 shows one such concept, where flexible arrays are rolled out from reels on the lander and affixed to the ground. The arrays are angled toward the east and west to provide power for both sunrise and sunset conditions as well as midday. The power system may also be on an unmanned supply vehicle and deployed automatically in advance of the piloted mission.

2. PHOTOVOLTAIC TECHNOLOGY

There are three approaches to large area photovoltaic arrays in space. The conventional approach, used on all existing satellites, is to make flat-plate arrays from individual crystalline solar cells. The material currently most widely used is silicon (Si); Gallium Arsenide (GaAs) solar cells, with improved efficiency, are also being flown, and Indium Phosphide (InP) solar cells, with a higher tolerance to radiation damage, are being developed for possible use in the future.

An alternative approach is to use solar concentrators with extremely high efficiency solar cells. Such an approach has yielded the highest conversion efficiencies achieved to date, over 30% AM0 using

a tandem GaAs/GaSb solar cell. The first spaceflight experiments with such high-efficiency concentrator solar arrays are now in progress.

A third approach is to use thin-film, integrally connected solar cells, adapting new technology which has been developed for use in low-cost terrestrial solar arrays. Materials used for such arrays include amorphous silicon, CdTe, and copper indium diselenide. This approach has the potential for low weight arrays, the possibility for low cost, and have been demonstrated to have extremely high tolerance to radiation, but is unlikely to achieve the high efficiencies found in single-crystal technologies. Nevertheless, recent advances in efficiency (Fig. 2) have been striking. This array technology has not yet been demonstrated in space, although individual solar cells have been tested in space, confirming the high tolerance to radiation.

Research is ongoing to increase the efficiency, lower the cost, and increase the specific power for all three of the approaches discussed.

3. SINGLE-CRYSTAL CELLS

Table 1 summarizes the AM0 efficiencies achieved in the laboratory of a variety of single junction solar cells. The current generation of space solar cells² consists of silicon cells. GaAs cells, somewhat more efficient than silicon cells, are beginning to be flown on certain advanced satellites where high efficiency is a major criterion. GaAs on Germanium (Ge) will be flown on the Earth Observing Satellite AM scheduled for launch in 1997.

While currently flying silicon solar cells only have an efficiency of about 14%, in the last decade tremendous advances have been made in silicon solar cell efficiency. Advanced silicon solar cells have been manufactured by the University of New South Wales and by Stanford University with efficiency approaching 21% AM0³. These solar cell designs are not yet space qualified, however, and preliminary tests indicate that they are not tolerant to radiation damage. Future designs ultra-thin, light-trapping cell designs may have the advantage of being both highly efficient and radiation tolerant⁴. A 100 μm Si cell was recently reported to have achieved an efficiency of 18.0 %⁵.

The state of the art silicon space solar cell is a large area (8 x 8) cm cell, 0.2 mm thick, covered with a 0.125 mm thick ceria stabilized glass microsheet. This cell, 10 $\Omega\text{-cm}$ base resistivity, with dual anti-reflective coating and a back surface field, has an average efficiency of 14.2% at 28°C, beginning of life (BOL). These cells are currently under production for Space Station Freedom².

The inherent higher efficiency potential for III-V solar materials such as GaAs and InP has promoted research leading to the production of research solar cells routinely in excess of 20%⁶. The desire to reduce cost and breakage has also led to production of III-V cells on other substrates⁷. The current cost of 2 inch semiconductor grade wafers for solar cell production is \$3.00 for silicon, \$65.00 for germanium (Ge), \$100.00 for GaAs, and \$200.00 for Indium phosphide (InP). The cost variations in the latter three are a reflection of supply/demand and not an intrinsic production difference. Current costs for GaAs/GaAs and GaAs/Ge cells are 3-5 times the cost/watt of the SSF solar cell. Cell manufacturing is moving toward thin (< 5 μm) high efficiency structures on low cost substrates. It is not unrealistic to envision the costs of future high efficiency cells approaching silicon cell costs. Cell cost however is only one component of the cost of an array. The mission profile could dictate requirements such that the higher efficiency array, and hence, less area, would be cost effective for the power system. For instance, replacing the silicon cell on SSF with a 22% efficient solar cell would provide a lower array cost and a considerable weight savings.

A recently-developed alternative single-crystal solar cell technology is indium phosphide (InP). InP solar cells potentially have an efficiency equivalent to that of GaAs, but with vastly superior

tolerance to radiation. A difficulty with InP, however, is the cost of the material. Several methods of growing InP on low cost substrates are currently under development. Missions requiring long lifetimes or high radiation orbits have led to the development of InP cells. The superior radiation resistance of InP cells is illustrated in Fig. 3. The mission chosen for the purpose of illustration is the earth observing satellite (EOS) orbit, which has approximately the same equivalent radiation fluence as the moon. Fig. 4 compares the total radiation fluence, neglecting solar flare events, for five years in a SSF orbit (334 km, 30°), EOS orbit (700 km, 100°), LIPS orbit (1100 km, 60°), and geosynchronous (GEO) orbit (35794 km, 0°). The lunar radiation environment is provided for comparison and will be discussed later.

A small module of InP solar cells on the LIPS satellite has shown no degradation after five years in space. Several thousand InP solar cells were produced by the Japanese and a thousand were used to power a lunar orbiter on board the ISAS scientific satellite "MUSES-A", launched in January, 1990.

Efficiencies listed in Table 1 for InP/Si and InP/GaAs are beginning efforts to produce a less expensive solar cell by growing the InP structure on a less expensive substrate. Efforts are also in progress to remove the thin (< 4 μm) InP solar cell structure from the substrate by mechanical techniques (CLEFT) and preferentially etched epitaxial liftoff⁸. Both of these techniques also apply to other III-V structures and hold great promise for future crystalline thin film solar cells.

4. CONCENTRATOR AND CASCADE CELLS

Table 2 lists the current status of two- and three-junction solar cells. These are small area cells which can be used in a variety of concentrator systems. Demonstrated efficiencies of over 30% have been achieved. In missions requiring minimum array area, concentrator arrays provide a promising alternative to planar structures. Concentrators also provide extra protection from the radiation environment. The pointing requirements for the mini-dome fresnel concentrator⁹ are $\pm 2^\circ$, which is an order of magnitude less stringent than required by a solar dynamic concentrating system. Utilizing an optical secondary, the mini-dome concentrator tolerance can be relaxed to $\pm 3.5^\circ$.

Cascade cell development has proceeded in both a mechanically stacked arrangement in which a lower bandgap solar cell is placed underneath an infrared transparent higher bandgap cell, and also in a monolithic structure in which the cells are often interconnected by tunnel junctions. The simplicity of simply stacking the cells is offset with the added wiring complexity. Future progress can be anticipated in both of these approaches, leading to a future 40% efficient tandem structure.

5. THIN-FILM SOLAR CELLS

An alternative to the conventional single-crystal solar cell is the thin-film solar cell. Thin-film solar cells are made from thin (1 to 5 micron) semiconductor layers deposited on an inert substrate or superstrate material. The semiconductors have a high-absorption constant; the high absorption constant allows essentially complete absorption of the light within the first micron or so of the material. Recently thin-film solar cells have been the topic of a considerable research effort for low-cost terrestrial electricity production. Initial research efforts focussed on amorphous silicon (a-Si); recently copper indium selenide (CuInSe_2) and cadmium telluride (CdTe) have shown extremely good experimental results. Fig. 2 shows the recent progress in efficiency of copper indium selenide and cadmium telluride cells.

For technologically well-developed materials, such as Si and GaAs, achieved efficiencies are very close to the theoretical predicted limits. For thin-film materials, achieved efficiencies fall well below these values. There are two reasons for this disparity. First, Si and GaAs have received the benefit of extensive materials development for the electronics industry and are technologically very well understood materials; thin-film materials have been comparatively little researched. Second, because

thin-film materials are polycrystalline or amorphous, there are additional sources of efficiency loss due to the effects of structural disorder and grain boundaries. It is not known whether the ultimate efficiencies of these materials can ever approach those of the single crystals.

In general, all of the thin-film solar cell types have exceptionally high radiation tolerance compared to conventional single-crystal cells. A review of radiation damage effects in thin film cells can be found in reference¹⁰.

In summary, the advantages of thin-film solar cells are: high radiation tolerance; high specific power; potentially in the kilowatt/kilogram range; large area solar cells with integral series interconnections; the potential for thin, flexible blankets; and low cost. The disadvantages of thin-film solar cells are: lower efficiency; lack of space experience; and the fact that they are not currently produced on lightweight substrates.

Reviews of thin-film solar cell research for terrestrial applications can be found in Refs. 11 and 12. Reviews of applications for space can be found in Refs. 13-15.

Experimental measurements on thin film solar cells are almost always quoted for a solar spectrum filtered by passage through the atmosphere (Air Mass 1.5, or "AM1.5" spectrum). Very few measurements have been made of cells under the space (Air Mass Zero, or "AM0") spectrum. Efficiency measured under space sunlight is lower than that under terrestrial sunlight because most of the added energy available in space is in the infrared and ultraviolet regions, to which solar cells are generally not very responsive. The conversion factor from AM1.5 to AM0 efficiency is typically a decrease in efficiency by 15 to 20 percent for cells with bandgaps in the range of interest, varying with the spectral response of the solar cell in question. For an amorphous Si cell, for example, conversion of AM1.5 efficiency to AM0 is by a multiplicative factor of 0.80¹⁶. For a copper indium gallium selenide (CuInGaSe₂) cell, an efficiency of 11.1% AM1.5 was measured as 10.0% AM0; resulting in a multiplicative factor of 0.90¹⁷.

While thin-film technologies have not yet been demonstrated in space, there is a very large (by space standards) manufacturing base on the Earth: tens of megawatts per year for a-Si, a rapidly increasing capability of perhaps one megawatt per year for copper indium selenide, and several hundred kilowatts per year for cadmium telluride.

The active regions of thin-film cells are typically a few microns, compared to several hundred microns thickness required for conventional silicon solar cells. The technology could potentially be extremely lightweight, if the cells can be deposited on lightweight substrates (or superstrates). However, current technology development programs are directed at glass substrates, inexpensive and rugged but not lightweight. There is little or no research on alternative, lightweight substrates. Some recent experimental work has been done on deposition of CuInSe₂ onto lightweight substrates. Researchers at Boeing have manufactured 4 cm² CuInSe₂ cells on 50 micron thick flexible glass substrates¹⁸. Kapur and Basol at International Solar Electric Corporation, under SBIR contract to NASA Lewis, are also investigating CuInSe₂ cells on thin substrates, including thin glass sheets, and have reported some significant results in work done on foils¹⁹. Technology to manufacture amorphous silicon solar cells on lightweight thin substrates has been demonstrated by several organizations, including ECD¹⁷ and Iowa Thin Film Technology Corporation²⁰. Sanyo Corporation has recently announced commercial production of amorphous silicon solar cells on flexible substrates under the trade name "Amorton," with a quoted specific power of 275 W/kg, AM1.5, corresponding to about 220 W/kg at AM0.

Flexible substrate a-Si arrays are not being made with fully space-qualified materials, and to date have not been tested under space conditions. There is some interest in lightweight, high specific-power

a-Si arrays for space ²¹; a recent review article ²² discusses production capability in the United States for a-Si spacecraft arrays.

An important technology for the production of future high-efficiency thin film arrays is the ability of thin films to be produced in multi-bandgap "cascade" structures. This could potentially allow efficiencies of 15 to 20%, with the light weight and high radiation tolerance characteristic of thin film cells ¹⁷. The best currently demonstrated thin-film cascade, reported by Siemens Solar²³, uses an amorphous silicon top cell on a CuInSe₂ bottom cell. The achieved efficiency is 12.5% AM0 (estimated from AM1.5 measurement). In this cell the two elements were deposited on separate substrates, and the two elements coupled with transparent encapsulant. For higher specific power, it would be desirable to eliminate the intermediate layer by depositing the a-Si cell directly on the CuInSe₂.

The potentially light weight of thin-film materials allow new strategies for solar power satellite design. Landis and Cull²⁴ have proposed using the potentially extremely light thin-film solar cell technology for reducing the mass of a solar power satellite by integrating the solar cells and a solid-state receiver. Such a technique could, potentially, decrease the mass of a solar power satellite by a factor of ten to a hundred. This approach requires considerable additional study before it could reach the stage of being ready for engineering design.

6. COST AND PRODUCTION READINESS

Despite revolutionary decreases in the cost of terrestrial solar cells, solar arrays for space applications have not decreased in cost significantly over the past twenty years. Space solar arrays currently cost on the order of \$1000 per watt, while terrestrial array costs are as low as \$2 per (peak) watt, with costs of under \$1/watt quoted as actual manufacturing costs for the generation of manufacturing plants currently under construction, assuming that the demand exists to run these plants at full capacity. For cost-competitive electricity, it is clear that a satellite solar power array would have to be much more like terrestrial array than the type of array currently used in space.

Space array costs are high because there is only a weak incentive to try to reduce them. Even at \$1000/watt, for example, the 6 kW array of an Intelsat-VI satellite represents only a small portion of the \$250M cost of building and launching the satellite.

Some of the cost difference between terrestrial and space arrays is due to the fact that space arrays use more efficient cells, have more stringent weight requirements, and have many more inspection steps to assure reliability. However, a significant portion of the cost of a solar array is the cost of interconnecting the cells. 2 cm by 4 cm cells are still in use on satellite arrays, considerably smaller than the 10 cm square and larger cells used in terrestrial arrays. In this respect the solar arrays for Space Station Freedom, using 8x8 cm cells and a simplified rear-side printed-circuit interconnect, is a considerable advance. Use of thin-film cells, with the interconnections made on large-area sheets at the same time as the cell manufacture, could also represent a means for considerably reducing this expense.

Over the last ten years, the terrestrial photovoltaic industry has made great advances in production capability, with single-crystal silicon, polycrystalline silicon, and amorphous silicon all having well over a megawatt per year of production capability, and with several factories recently announced to produce both cadmium telluride and copper indium selenide on a multi-megawatt scale. Figure 5 shows the historical trend of world shipments of photovoltaic generating capacity. While the production capability is large and growing, the cumulative production of solar panels in the last twenty years only totals slightly over 300 MW(p), or roughly the power capacity of a single fossil-fuel powered electric plant. Note also that solar cell production quantities are quoted in terms of peak megawatts, the power which would be produced with the sun directly overhead. Actual power production, on the Earth's surface, is considerably lower, due to night and cloud coverage.

(On the same graph, the world usage of solar cells for space, well under one megawatt per year, would not even be visible.)

7. ARRAY TEMPERATURE

A solar array on the moon will operate at significantly higher temperature than arrays in near-Earth space. Solar array operating temperatures are determined by an energy balance equation, where the incident energy minus the energy converted into useful power is radiated thermally according to the fourth-power of temperature as specified by the Stefan-Boltzmann radiation law. The lunar soil is a quite good thermal insulator, and thus the solar array will be able to radiate to space only from one side. The operating temperature on the moon can thus be estimated from operating temperatures in high orbit by assuming that the solid angle available for radiation is cut in two. The maximum operating temperature on the moon will be increased by about 19%. Since typical operating temperatures for geosynchronous orbit arrays are $\sim 305^\circ\text{K}$, this yields a maximum operating temperature of 90°C (decreasing slightly if the cell efficiency increases). This is very close to the temperatures reached by the lunar surface at local noon.²⁵ Average daytime power will be somewhat lower.

These numbers are roughly consistent with those measured by instrument packages left on the moon during Apollo. For example, the Apollo 11 PSEP package reached a maximum temperature of 88°C at lunar noon.²⁶ Similarly, the Apollo 12 Surface Magnetometer reached a maximum external temperature of about 78°C .²⁷ Fig. 6 shows a graph of measured instrument temperature versus time for one lunar day.²⁷ The average daytime temperature is lower than the noon maximum, but still considerable higher than nominal.

The large areas required for the solar array make it unlikely that cooling techniques will be usable. Since solar cell performance decreases with increasing temperature, a consideration in the selection of the solar cell type is to select a solar cell material which is not highly sensitive to temperature. The temperature dependence is primarily dependant on the bandgap of the material, with lower temperature sensitivity for wide-bandgap materials, such as GaAs or amorphous silicon. If the bandgap can be increased, as by going to a ternary III-V compound such as AlGaAs, the temperature sensitivity is decreased yet further, although at some cost in decreased efficiency at standard temperature. Cascade (or "tandem") cells also have high temperature sensitivity, typically equal to the sum of the sensitivities of the individual component cells, and are thus less desirable for lunar use, although of higher baseline performance at standard temperature.

The temperature variation of power ($1/P \partial P/\partial T$) for gallium arsenide cells is about $0.25\%/^\circ\text{C}$.^{28,29} For cell operation at 90°C , the power would be derated by about 17% due to temperature. Amorphous silicon would be comparable or slightly better. For silicon, the temperature variation is about $0.33\%/^\circ\text{C}$,²⁸ leading to about 23% loss, with CuInSe_2 expected to be about the same.

For the single crystal solar cell technologies, GaAs and Si, the temperature extremes are not expected to present lifetime problems if adequate design safeguards against thermal cycling are taken. For thin-film technologies, long-term operation at high temperatures and vacuum thermal cycling stability have not yet been demonstrated, and reliability will have to be verified before such arrays can be used on the moon.

8. RADIATION ENVIRONMENT

The moon has no permanent magnetic field; hence there are no trapped radiation belts. The major source of natural particle radiation for an array on the lunar surface is solar flares which consist predominately of protons. Solar flares occur sporadically with varying magnitudes over an eleven year

cycle. The effect of solar flare protons has been calculated statistically. A comparison of a five year total equivalent 1 MeV electron fluence for a lunar SSF solar cell versus an earth orbit SSF solar cell (5 mil (125 μ m) coverglass) is shown in Fig. 4. During the lunar night, when the moon is between the sun and the array, the array will be protected from solar flare protons. This has the effect of reducing the flux by a factor of two and has been taken into consideration for Fig. 4.

9. STORAGE TECHNOLOGY

Solar power is an abundant resource during the lunar day. The 354 hour lunar night, however, poses a large obstacle to implementation of an all solar-powered lunar facility. Power storage concepts include conventional options such as batteries or fuel cells; less common storage technologies such as inductive or capacitive storage, possibly using superconductive elements; and physical storage concepts such as flywheels and compressed gas³⁰. Present technology storage capability is about 25 W-hr/kg for Ni-H batteries. Levels of ~80 W-hr/kg are expected for composite flywheels, and 300 W-hr/kg for regenerative fuel cells with conventional reactant storage. Up to 1000 W-hr/kg is expected for advanced RFCs if the conventional pressurized gas reactant storage is replaced with cryogenic storage³¹. Storage efficiencies (ratio of energy in during charging to energy out at night) is typically on the order of 60-70% for existing systems. Values of 80% should be achievable.

Finally, a lunar base could utilize a hybrid power system, with an isotope power supply to provide a baseline power level both during the day and night, and a photovoltaic power supply for peak power during the day.

10. SYSTEM INTEGRATION

We will not consider the balance of system, or power conditioning and management system, in any detail, but simply assume that the balance of system mass (excluding the storage system) is equal to three times the actual array mass. This assumption is based on the space-station *Freedom* power system design, where a 75 kW power system is assumed. A rough breakdown of the power system mass for *Freedom* is shown in table 3. We believe that this is likely to be a conservative estimate, and that advances in power system components, experience with large space power systems learned from the *Freedom* system, and careful attention to system mass may be able to reduce this mass considerably.

We also note that, for existing ultra light-weight array designs (e.g., APSA³²), the structural elements of the array are roughly equal in weight to the solar cell blanket. This structural mass has been factored into the array masses shown, however, we should note that a good analysis of the structural mass required on the moon will have to wait until details of structure, tracking (if used), and deployment mechanisms have been selected. An array designed for the 1/6 g environment of the moon may be considerably different from typical arrays designed for free-fall deployment.

Table 4 shows a conceptual design for a baseline photovoltaic-powered lunar base, with a mass breakdown of the primary elements.

Three cases are shown: present-technology baseline case, with thin silicon cells and Ni-H batteries, conservative next-generation technology, with advanced thin, 20% efficiency GaAs solar cells and regenerative fuel cells for storage, and advanced technology thin-film cells with advanced fuel cell technology and cryogenic reactant storage. The total mass is calculated for a 100kW daytime power requirement and 50% night power, with the assumption of 80% storage efficiency (energy out/energy in). This efficiency is somewhat higher than is achievable using current technologies.

From these figures it is clear that storage technology, and not photovoltaic technology, dominates the total mass of the power system.

A solar array for the moon can be configured either as a sun-tracking array or as a fixed array. On the equator, a tracking array has higher total energy production than a fixed horizontal array of the same size by a factor of $\pi/2$, or about 57% more energy. The advantage increases as the base is moved further away from the equator. This advantage is likely outweighed, however, by the added structural mass, complexity, and deployment difficulty of the tracking system. The tracking array has an important additional advantage: the power profile is nearly flat, while the fixed horizontal array has a power profile proportional to the cosine of the solar angle, peaking at solar noon. These are shown in figure 6. Since this means that a fixed horizontal array will produce zero output at sunrise and sunset, the amount of time that power must be provided by the storage system is significantly increased. Since the power storage mass dominates the system mass, an array which does not produce baseline power immediately after sunrise is not acceptable.

To increase the power at sunrise (and sunset) yet still eliminate the complexity of a tracking array, the array can be peaked as shown in figure 7. We set the requirement that the power be provided by the array rather than by the storage system immediately starting at sunrise and continuing until sunset. The required angle to provide this power profile is discussed in the next section.

11. OPTIMUM ARRAY ANGLE

Consider an array consisting of two identical panels, each tilted an angle a from the horizontal, respectively toward sunrise and sunset. If the rated array power at normal incidence is A , and q is the sun angle with $q=0$ defined as solar noon, the power for the tilted array is:

$$P = A \cos(a)\cos(q) \quad \text{for } |q| < p/2 - a, \quad (1a)$$

$$P = (A/2)\cos(a)\cos(q) + (A/2)\sin(a)\sin(q) \quad \text{for } (p/2 - a) < |q| < p/2, \quad (1b)$$

$$\text{and} \quad P = 0 \quad \text{for } |q| > p/2. \quad (1c)$$

Thus, the average power over the daytime is:

$$P_{ave} = [\cos(a) + 1] / p \quad (2)$$

which, as should be expected, has a maximum value of $2/p$ for $a = 0$, a horizontal array. (For comparison, for a tracking array $P_{ave} = 1$). The power at sunrise equals the power at sunset,

$$P_{sunrise} = \sin(a)/2. \quad (3)$$

Consider energy storage with an efficiency h (energy out/energy in) and power fraction f (power required at night divided by power required during the day). Then the average power generated during the day P_{gen} must be larger than the daytime load by a factor k :

$$P_{gen} = (1 + f/h) P_{day} \int k P_{day} \quad (4)$$

where we have defined $k = (1 + f/h)$. To minimize the storage, we require that the array power at sunrise equal the daytime load P_{day} , *i.e.*, immediately at sunrise no power is drawn from the storage system. This then gives us an equation for the minimum array tilt angle a :

$$\sin a = 2 (\cos a + 1)/(p k) \quad (5).$$

The solution to this equation is:

$$a = \cos^{-1} [(k^2 - 4/p^2)/(k^2 + 4/p^2)] \quad (6).$$

As an example, suppose night and day power requirements are equal, and the energy storage efficiency is 100%. Then the sunrise power must be exactly half the average (daytime) power, and the minimum angle a is:

$$a = \cos^{-1} [(p^2 - 1)/(p^2 + 1)] = 35.3^\circ \quad (7).$$

From equation 2, the array considered provides 58% of the power per unit area of a tracking array. This is shown in figure 3, which compares the power versus time profile for a peaked array at 35.3° with the power profile of a tracking array and a fixed horizontal array.

For a more realistic example, suppose the required night power is half the daytime power, and the storage efficiency is 85%. Then $f/h = 0.588$, and the optimum angle $a = 43.7^\circ$. This is still 55% of the power per unit area of a tracking array. As can be seen, the required angle increases as f/h decreases.

12. ALTERNATIVE CONCEPTS FOR LUNAR NIGHT POWER

The dominance of storage mass over the photovoltaic array mass for the lunar night is so large that it may be worth considering alternate methods of storage or of powering the base over the night. A general survey of such methods is considered in reference 30. The methods proposed consist generally of alternative methods of power storage, which will not be discussed here, and methods of continuous solar power generation over the night. Of the continuous power generation methods, we discuss here one concept for illuminating the solar arrays continuously.

One proposal is to use beamed power to run the base during the night. As a specific example, the solar arrays could be illuminated from the Earth by laser. For an array of 50 kW required night power, using stationary reflectors on the moon to concentrate light onto the arrays, 2.2 MW of Earth-based lasers operating at a wavelength of 0.5 microns would be sufficient to run the base if the solar cells selected were an AlGaAs alloy of bandgap 2.0 eV. Assuming two meter diameter lenses (which may be fresnel lenses or holographic optical elements), the beam spread at the moon is diffraction limited and illuminates a spot a hundred times larger than the array, allowing considerable growth in power required before the ground-based lasers need to be upgraded. To eliminate single point failure, many ground lasers could be used. While the technology for making high-power continuous wave lasers at wavelengths as short as 0.5 microns is not now commercially available, the technology is rapidly advancing, and may very well be available by the time a moonbase is emplaced.

13. IN-SITU PRODUCTION

For an expanded lunar facility, it may be practical to manufacture power sources from in-situ resources. Cells made from InP, GaAs, CuInSe₂, and CdTe are ruled out for lunar production due to material scarcity. Silicon, however, is abundant, as well as array structural materials aluminum, titanium, steel, and glass. While hydrogen, carbon, and halogens are required for existing Si refining and purification processes, an aluminothermic process sequence for production and refining of Si from lunar anorthite is possible which reuses all reactants. Production of both amorphous (a-Si:H) and single-crystal cells on the moon is possible³³.

The production sequence for a-Si:H cells is comparatively simple. The required thickness of amorphous silicon is very small, allowing high specific power and a low requirement for refined Si.

Disadvantages are the comparatively low efficiency, light-induced degradation; and the requirement that the refined silicon be converted into silane for use.

Single crystal silicon, the workhorse of the current spacecraft solar array industry, has higher efficiencies but greater material usage. The production sequence is energy intensive; however, most of the requirement is heat, which could be provided by inexpensive solar furnace.

Likewise, power storage capability may be manufactured from available materials. While hydrogen is not easily available to use as reactant in hydrogen/oxygen fuel cells, oxygen will be a major product of any lunar industrial facility. Lunar derived steel and fiberglass will also be available to make tanks for (non-cryogenic) reactant storage. Alternately, flywheels could be manufactured from lunar-manufactured glass fiber, with specific energy of perhaps 20 W-hr/kg. This is somewhat lower than is possible with advanced composites (e.g., Kevlar™), but will require little non-local material usage. The lunar vacuum, low gravity, and plentiful availability of regolith for failure protection make flywheel storage a viable alternative for night storage.

14. CONCLUSIONS

Use of photovoltaics for the primary power system for a lunar base presents several issues for consideration. A reference photovoltaic power system for a lunar base has been outlined, and the effect of anticipated technology advances discussed. The primary consideration for power system mass is the requirement for 14 days of storage for operation of the base over the lunar night. It will be important to minimize the power requirement during the night using techniques, for example, such as separating and storing the waste carbon dioxide for regeneration during the day when surplus power is available. Hydrogen/oxygen fuel cells, preferably using cryogenic storage of the reactants, are a critical technology to reducing the mass of the storage system. In order to minimize daytime storage requirements by transitioning from stored power to use of directly generated power as quickly as possible after sunrise, an array design which is peaked toward the east and west was proposed.

Current photovoltaic technology is adequate for such a base, and anticipated advances such as thin-film solar cell development will reduce the array mass to a minor fraction of the total power system mass. Photovoltaic arrays will be required to operate at peak temperatures of up to 90°C, and to withstand nighttime thermal cycling at very low temperatures.

Finally, other proposals for power over the lunar night were briefly reviewed, and various possibilities for use of in-situ resources for manufacturing elements of power and power storage equipment were discussed.

15. REFERENCES

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Cell Type	Area(cm²)	Laboratory Efficiency % at 25°C	Projected Efficiency % at 25°C
8 mil Si	64	14.6	17
2 mil Si	8	13.5	16
Advanced Si	4	20.8	21
GaAs	4	21.8	23
GaAs/Ge	4	20.5	23
InP	4	19.9	22
InP/Si	4	7.0	19
InP/GaAs	4	13.7	21
Ge	4	9.0	10
GaSb	.234	6.9 (52X)	8 (52X)

**Table 1. Status of Single Junction Solar Cells
(AM0 Record Efficiencies to Date)**

I. Monolithic (Two Junction)

A. One Sun :

Top Cell/Bottom Cell	Area(cm ²)	Laboratory Eff. % at 25°C	Projected Eff. % at 25°C
AlGaAs/GaAs n/p n/p (two terminal)	.5	23.0	26
GaInP/GaAs n/p n/p (two terminal)	.25	23.6	26

B. Concentrator

Top Cell/Bottom Cell	Area(cm ²)	Laboratory Eff. % at 25°C	Projected Eff. % at 25°C
GaAs/Ge p/n p/n (two terminal)	.136	23.4 (9 suns)	33.5 (100 suns)
InP/Ga _{0.47} In _{0.53} As n/p p/n (three terminal)	.065	28.8 (40.3 suns)	30.0 (100 suns)

II. Mechanically Stacked (Two Junction)

A. One Sun :

Top Cell/Bottom Cell	Area(cm ²)	Laboratory Eff. % at 25°C	Projected Eff. % at 25°C
GaAs/CuInSe ₂ n/p n/p (four terminal)	.5	23.1	33.5 (100 suns)

B. Concentrator:

Top Cell/Bottom Cell	Area(cm ²)	Laboratory Eff. % at 25°C	Projected Eff. % at 25°C
GaAs/GaSb p/n p/n (four terminal)	.05	30.8 (100 suns)	33.0 (100 suns)

III. Monolithic/Mechanically Stacked (Three Junction)

A. One Sun:

Top Cell/Bottom Cell	Area(cm ²)	Laboratory Eff. % at 25°C	Projected Eff. % at 25°C
AlGaAs/GaAs/InGaAsP n/p n/p n/p (two terminal)	.5	25.2	30.0

**Table 2. Status of Two- and Three- Junction Tandem Solar Cells
(AM0 Record Efficiencies to Date)**

<i>Element</i>	<i>Mass (kg)</i>	<i>Fraction (%)</i>
PV Blanket	890	24.0
mast	330	8.8
gimbal	540	14.5
electrical equip.	610	16.6
thermal control	730	19.6
<u>misc. integration</u>	<u>610</u>	<u>16.5</u>
<i>total</i>	<i>3710</i>	
<i>not including:</i>		
Batteries:	1300	
Charge/disc. unit	290	

*Array is a quarter of system mass
array plus structure is half of system mass*

Table 3. Space Station *Freedom* Photovoltaic Power System Mass Breakdown per module (28 kW power produced; 18.75 kW av. user power)

Solar Array	cell type	thickness (μm)	efficiency (%)	spec. power (W/kg)	array mass (kg)	total mass (kg)
Present technology	Si	62	13.5	130	312.5	1250
Next-generation	GaAs	6	18.5	300	135	538
Advanced	Cascade	12	25	450	90	363
In-situ resource	a-Si	2	10	100	405	1625
Storage	type			specific energy (W-hr/kg)	mass (kg)	
Present technology	Ni-H batteries			14	600,000	
Next-generation	RFC, conv. storage			300	27,500	
Advanced	RFC, cryo storage			1000	7,765	
In-situ resource	composite flywheel			20	420,000	

mass is calculated for a 25 kW daytime power requirement and 50% night power, with the assumption of 80% storage efficiency.

Table 4. 25 kW Photovoltaic Power System for a Lunar Base (Including Balance of System mass = 3 times the array mass)

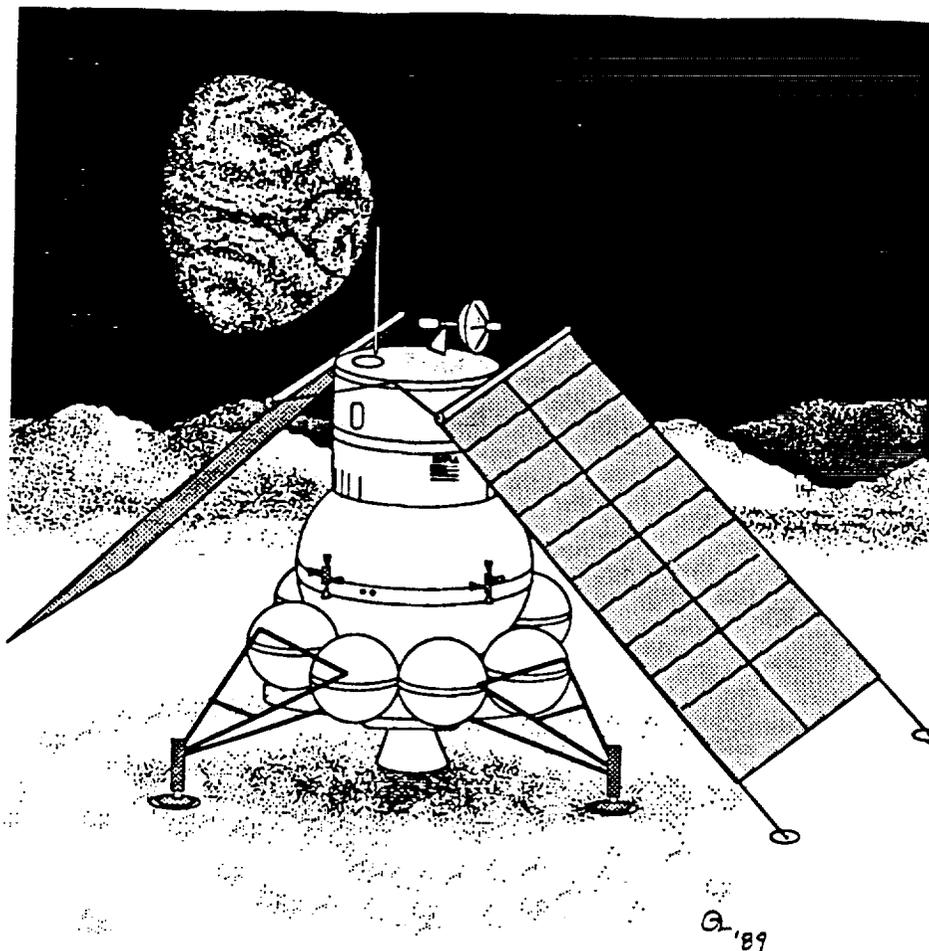


Fig. 1. Artist's conception of a fast-deployment roll-out solar array from the lunar lander.

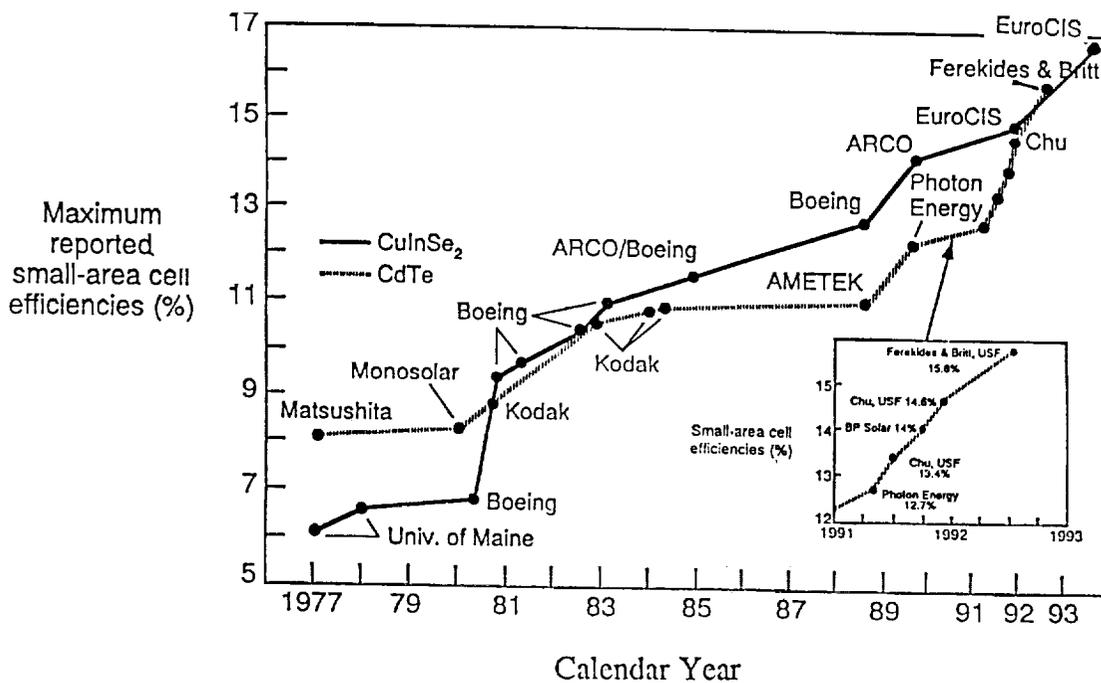


Fig. 2. Reported Air-Mass 1.5 efficiencies of small-area thin-film solar cells
 Solid line: Copper indium diselenide cells
 Dashed line: Cadmium telluride cells
 (Data courtesy of NREL. Note: Arco Solar is now Siemens Solar Inc.)

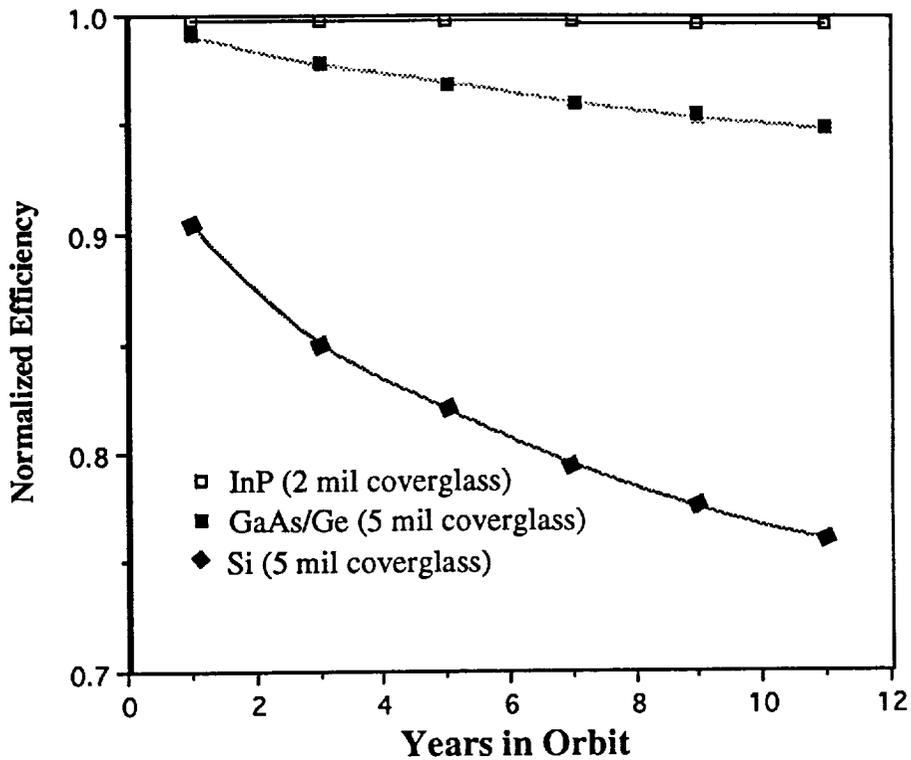


Fig. 3. Normalized Efficiency as a function of the number of years in a 705 km polar orbit

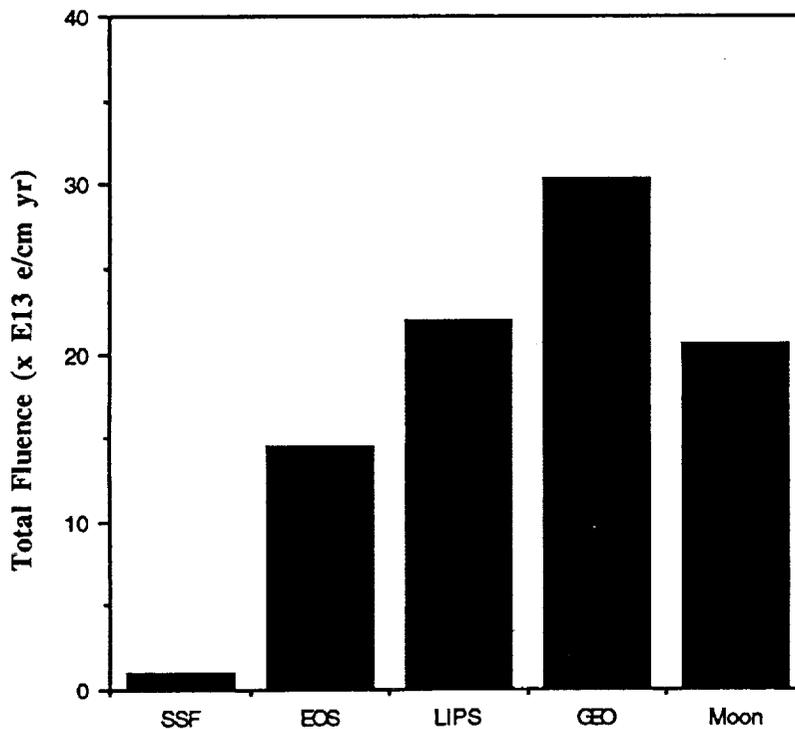


Fig. 4. Five Year Total Fluence, neglecting solar flare events for SSF, EOS, LIPS, & GEO, experienced by a SSF solar cell

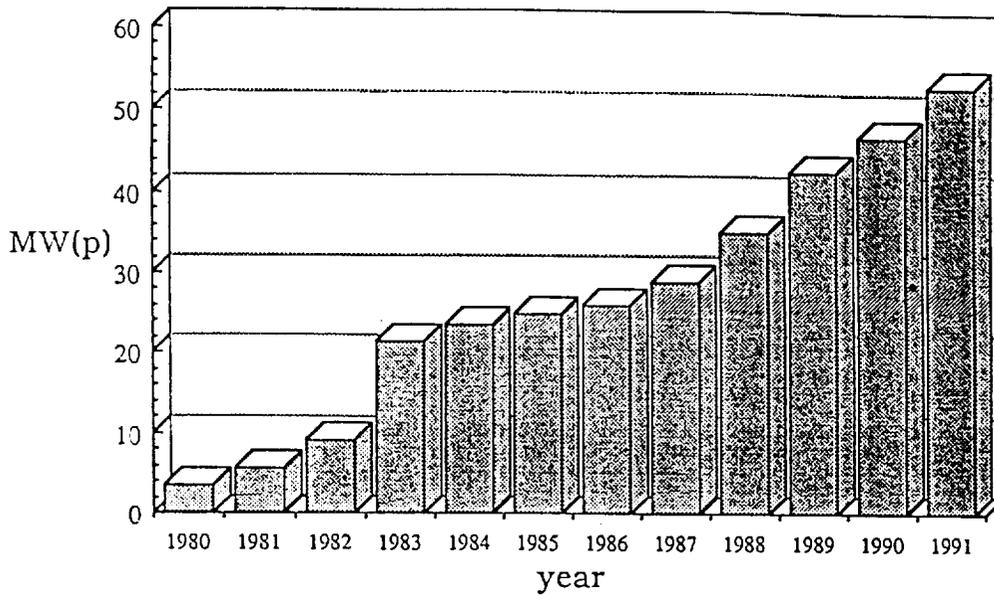


Fig. 5. World Photovoltaics Shipments, 1980-1991.

Growth in production capability of the world photovoltaics industry in Megawatts (peak) from 1980 through 1991. Includes solar cell applications in consumer electronics (watches, calculators) as well as utility and remote power applications. On this scale, the portion of production used for space applications (less than 1 MW) is not visible.

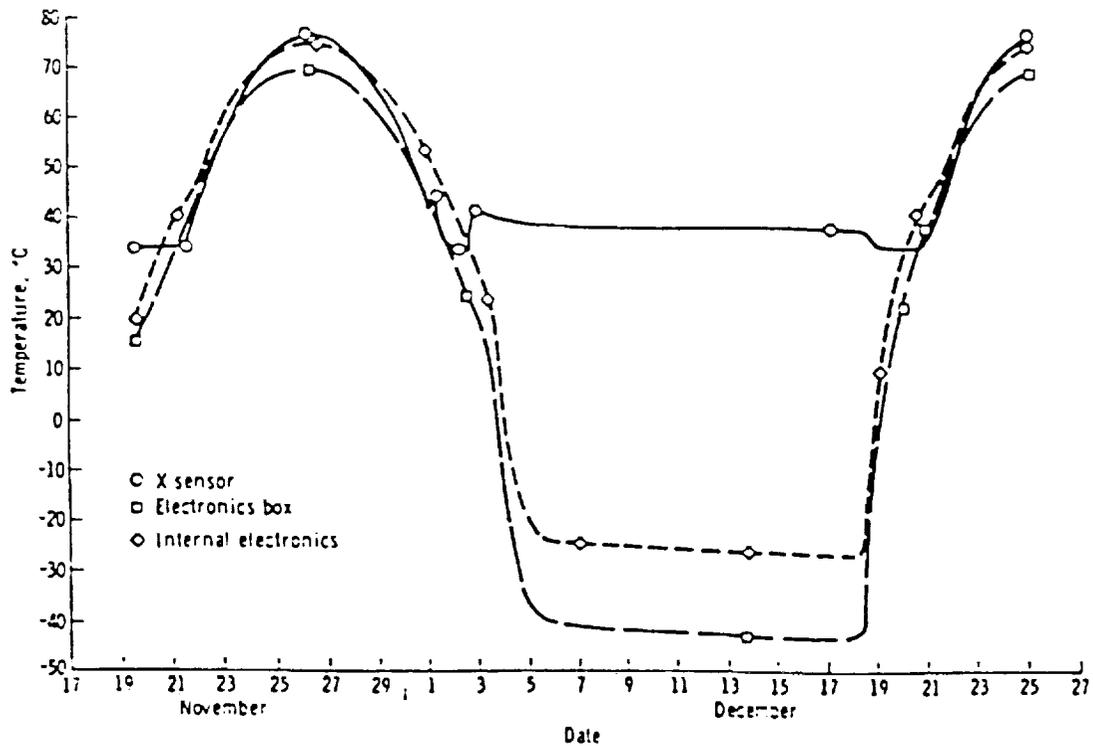


Fig. 6. Temperature versus time for Apollo 12 scientific package (note that night temperature is stabilized with a heating unit).

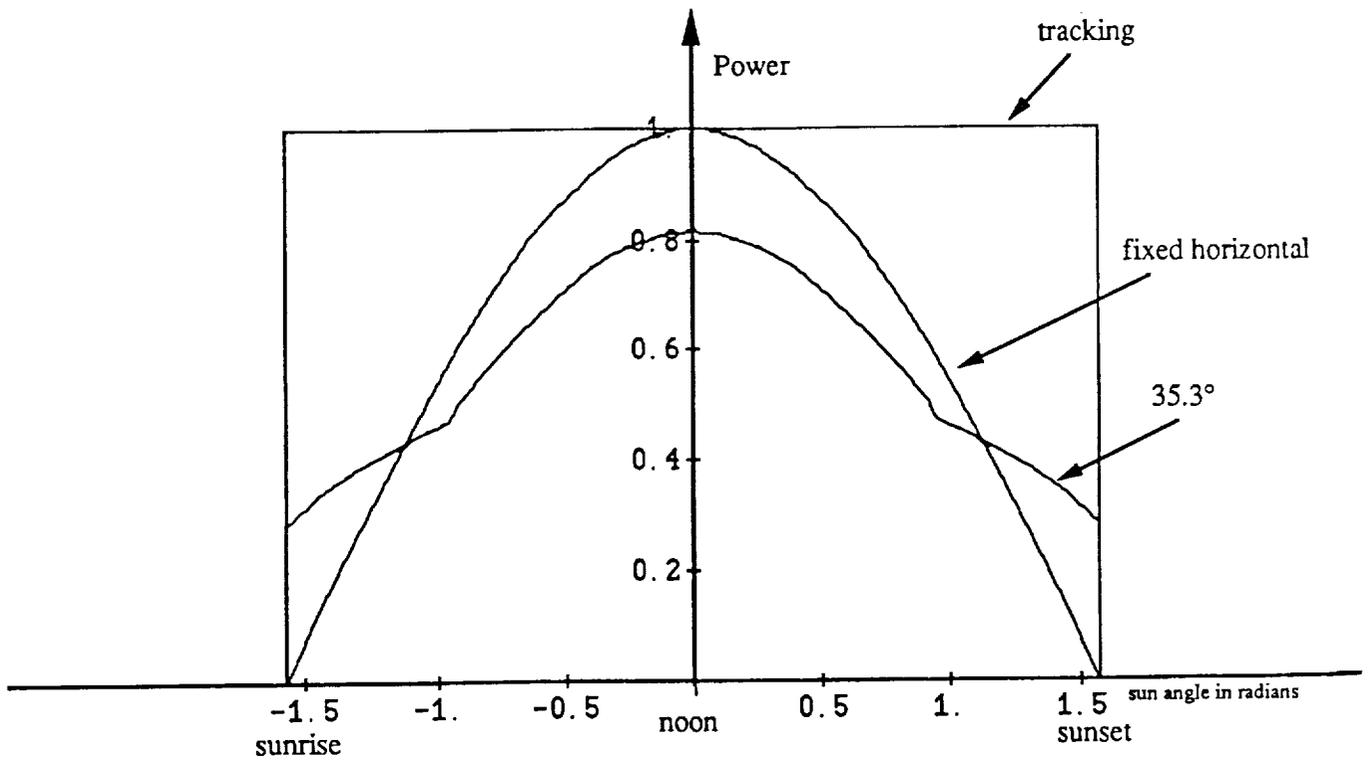


Fig. 7. Array output versus time for tracking array, fixed horizontal array, and double-tilted array at a tilt angle of 35.3° .

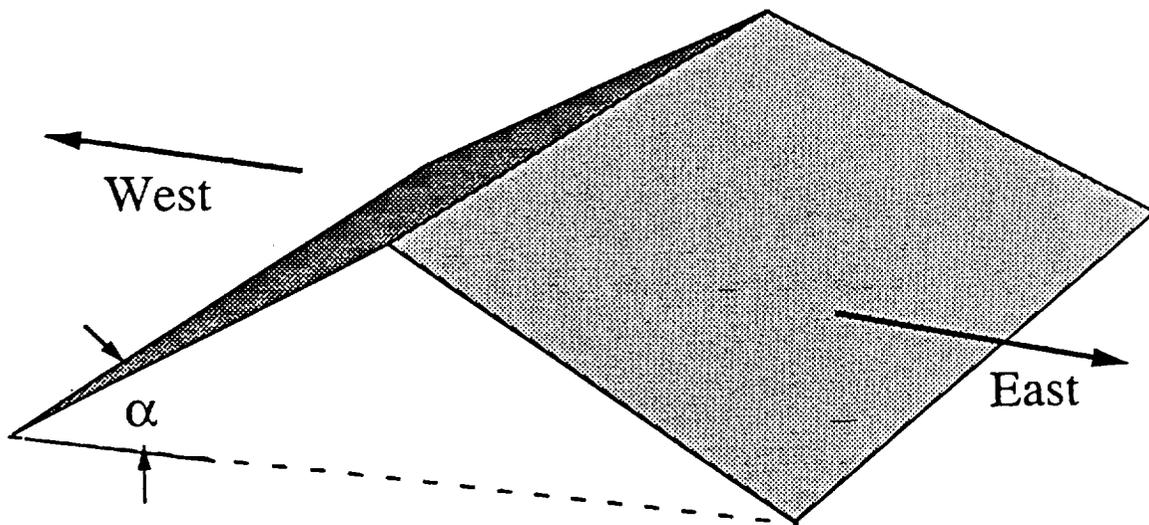


Fig. 8. Optimum two-tilt array for minimizing storage